

Acoustic Measurements of Tiny Optically Active Bubbles in the Upper Ocean

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LONG-TERM GOALS

In this project, which is closely linked to a separate project where the goal is to measure wave induced bubble clouds and their effect on radiance in the upper ocean (N000140710754), we are addressing the disturbing fact that despite the fundamental importance of optical backscatter in the ocean it is still not possible to explain more than 5 to 10 percent of the particulate backscattering in the ocean based on known constituents even during periods with no active wave breaking. In this project we want to check the hypothesis that very small bubbles that have been stabilized by surfactants may be responsible for part of the “missing” optical backscatter. This is accomplished by the development and use of broad-band acoustical resonator instrumentation.

OBJECTIVES

The main objective was to improve on an existing instrument design to allow for *in situ* measurements of bubbles over a wide range of bubble radii from approximately 500 micrometer at the upper end and down to less than 3 micrometer. We now have three systems where we obtain data at frequencies as high as 1MHz, corresponding to a smaller bubble radius limit of 3 micrometer. These systems were incorporated into the RadyO Scripps Pier experiment in January 2008 and ocean experiments in Santa Barbara channel during September 2008 and off Hawaii in September 2009. The systems have also been used successfully in two smaller experiments (East Sound, Washington and Duck North Carolina) to collect simultaneous optical and acoustical bubble size distribution measurements for assessment of differences, strengths and weaknesses associated with the different scientific approaches.

This work has been a collaborative effort between the IOS team and Helen Czerski and David Farmer at University of Rhode Island and with Mike Twardowski at Wetlabs.

APPROACH

Active acoustic techniques are commonly used to measure oceanic bubble size distributions, by inverting the bulk acoustical properties of the water (usually the attenuation) to infer the bubble population. Acoustical resonators have previously been used to determine attenuation over a wide range of frequencies (10-200 kHz) in a single measurement, corresponding to the simultaneous

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measurement of a wide range of bubble sizes (20-300 micron radii) (Farmer, Vagle, and Booth, 1998; 2005). By utilizing the broadband sensitivity of the resonator both resonant and off-resonant contributions to acoustic properties over a wide frequency range provide data that are inverted to recover the distribution of bubbles of different sizes within the cavity. The instrument operates at low signal intensity, justifying application of linear acoustical theory to the inversion. Near-continuous transmission of sound into the cavity avoids uncertainties in the time dependent acoustic response of bubbles to short pulses and multiple reflections of the reverberant signal increase the effective signal-to-noise of the device.

In our attempt to make measurements of optically active bubbles which have radii much less than the previous limit of $\sim 16 \mu\text{m}$ the instrumentation had to be modified to operate at much higher acoustical frequencies ($> 1\text{MHz}$). During the development of such a device, it turned out that several new challenges had to be overcome, both of technical and data analysis nature.

WORK COMPLETED

An example of a modern high-frequency acoustical resonator developed as part of this project for measurements of bubble radii between $\sim 3 \mu\text{m}$ and $400 \mu\text{m}$ is shown in Fig. 1. A typical example of the resulting acoustical spectrum from bubble-free water has also been included.

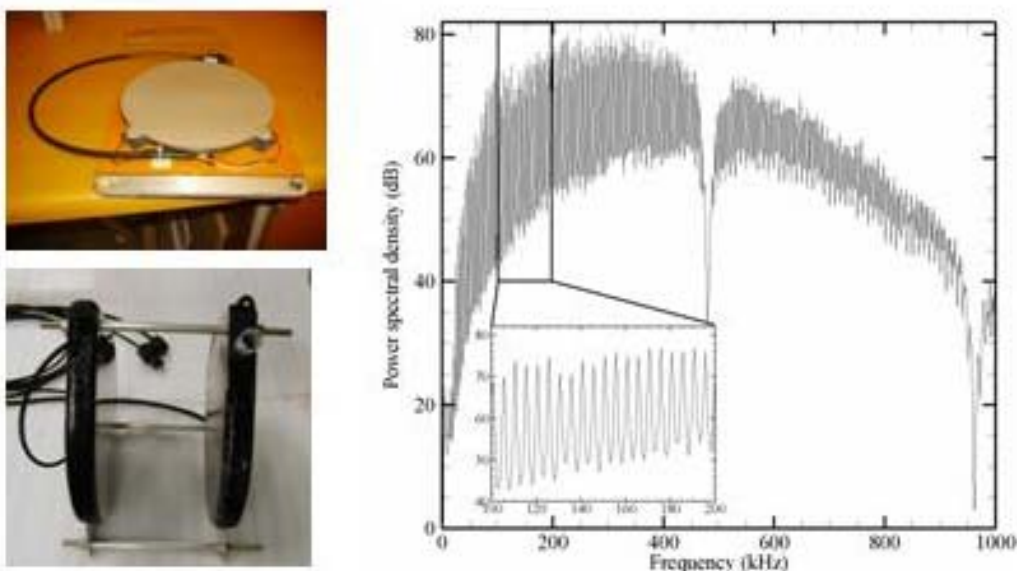


Figure 1. *Acoustical transducer developed as part of the RadyO DRI, capable of frequencies $> 1\text{MHz}$ (upper left), an assembled resonator system (lower left), and an example of the spectral output of this resonator system (right panel). The inset shows the section between 100 and 200 kHz, illustrating resonant peaks every $\sim 6\text{kHz}$. Detectable amplitude changes in each of these peaks are associated with bubble concentrations at a specific bubble radius.*

Technical challenges solved as part of this project

Even though we had significant experience in the development and use of acoustical resonators operating in the frequency range of 4-200 kHz, it turned out that when driving the transducers at frequencies at or above 1 MHz, several new technical challenges appeared.

While driving the transducers at these high frequencies the connectors separated from the piezoelectric film used to convert electrical to acoustical energy. Also, the compound used to waterproof the transducers became opaque to these high frequencies. Thirdly, the epoxy used to glue the piezoelectric film to steel and aluminium backing and reflection plates affected the acoustic field at high frequencies. Finally, electrical noise in the system, that was not a problem in earlier low-frequency versions of the systems became significant when dealing with the very small acoustical signals associated with small bubbles at high acoustical frequencies.

Eventually all these problems were overcome by getting the manufacturer of the piezoelectric film to mechanically add connectors to the film, by switching to different potting compounds, use low viscosity epoxies in the manufacturing process and to careful and painstaking efforts into reducing the electrical noise of the systems.

Modified and improved inversion algorithms for processing of high-frequency resonator data

To extend the bubble population measurement to smaller radii using this technique, it was necessary to extend the attenuation measurements to higher frequencies. Although the principles of resonator operation do not change as the frequency increases, the assumptions previously made during the spectral analysis were as part of this project now found to perhaps no longer be valid. For example, the resonant peaks (Fig. 2) at higher frequencies have a significantly lower quality factor (the ratio of the resonant bandwidth to the frequency at the resonant peak) than at lower frequencies. The cyclical nature of the spectrum produced by an acoustical resonator means that this description is no longer appropriate when the bandwidth becomes a significant fraction of the frequency increment between peaks.

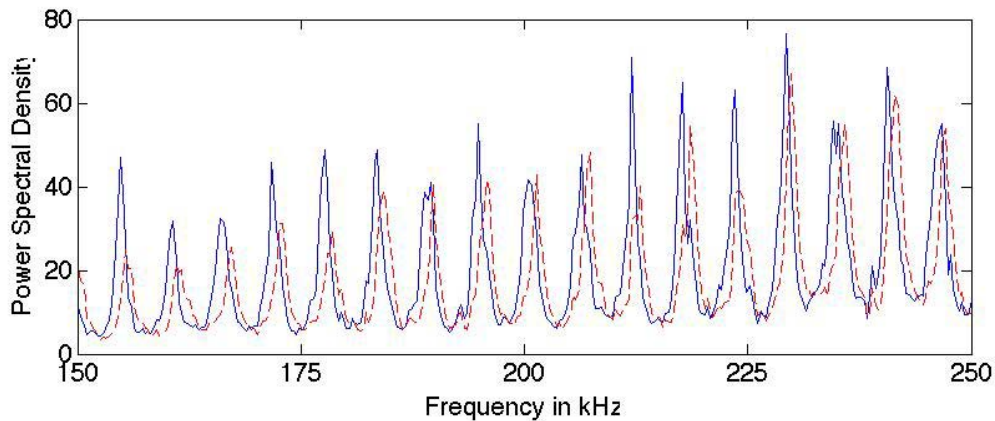


Figure 2. *The solid line shows a typical bubble-free spectrum over the frequency range from 150 to 250 kHz. The dashed line shows an attenuated spectrum from the same resonator during an ocean deployment. The presence of bubbles reduces the peak height and introduces a phase shift so that the peaks move sideways slightly.*

In order to improve on the methods used to calculate attenuation from acoustical resonator outputs, we developed a more complete analysis approach for the resonator operation using the eigenvalue of the resonance as a better measure of the strength of the resonant peak which allows for robust attenuation measurements over a much wider frequency range, and enables accurate measurements from lower-quality spectral peaks (Czerski et al., 2010). Figure 3 shows an example of eigenvalues used and the resulting model power spectral density as obtained from this analysis.

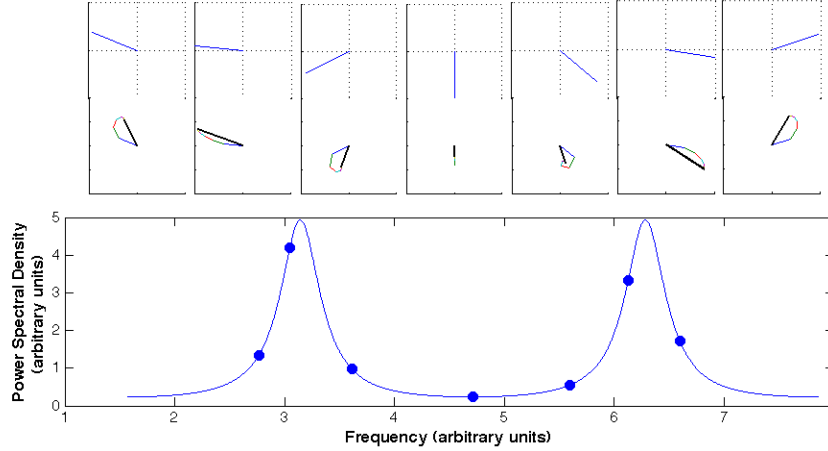


Figure 3. *The lower plot shows a model power spectral density, based on the eigenvalues depicted in the seven panels above it. Each blue dot on the lower plot corresponds to a pair of eigenvalue diagrams in the top seven panels. The upper lines in the top panels show the eigenvalue for that frequency on the complex plane. The second row of lines shows how the successive reflections sum to form the total pressure magnitude associated with that particular frequency. The thin lines represent the vectors that are summed to get the total pressure magnitude and the thick black line on each summation plot shows the total pressure magnitude.*

The data collected using these high-frequency acoustical resonators in the different RadyO field campaigns are presently being analysed using these algorithms to finally get to the upper ocean bubble size distributions and their variability and functional relationship to other environmental parameters.

IMPACT/APPLICATIONS

This effort will provide more detailed information about the presence and number of smaller bubbles in the upper ocean and their potential role in optical scatter.

RELATED PROJECTS

The development of a high-frequency, tiny bubble detection device is being utilized in the closely associated RadyO project N000140710754. In this project the goal is to invert the resonator data using the algorithms developed here and investigate the upper ocean bubble field under a range of different wind and wave conditions and in waters containing different surfactant concentrations.

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